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RESEARCH MEMORANDUM

A CORRELATION OF TWO-DIMENSIONAL DATA ON LIFT COEFFICIENT AVAILABLE WITH BLOWING-, SUCTION-, SLOTTED-, AND PLAIN-FLAP HIGH-LIFT DEVICES

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NATIONAL ADVISORY COMMITTEE FOR AERONAUTICS

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SUMMARY

A correlation has been made of the available data on various flap-type high-lift devices. The data are presented in two-dimensional form for flap-chord ratios varying from 20 to 40 percent. Included in the correlation are data for plain, single slotted, and double slotted flaps, and for suction and blowing flaps, which utilized boundary-layer control by suction and by jet flow, respectively. The correlation is not intended for design data but mainly to determine the relative merits of the various systems in providing lift, to provide general trends, and to provide sources of available data.

Results of the correlation from limited available data have indicated that for a given flap-chord ratio, the largest increments of lift coefficient at zero angle of attack were obtained for the blowing-flap configuration. Next, and in the order of decreasing ability to provide lift, was the suction flap, the double slotted flap, the single slotted flap, and the plain flap. The ability of a double slotted flap to provide lift was found to be closely related to the size of the vane ahead of the flap. Good agreement was obtained between the available blowing-flap data from various sources when the momentum coefficient is used as the parameter for correlation. Lift coefficient for the blowing flap, when presented as a function of momentum coefficient generally extended through two regions: a region of initial rapid increase in lift coefficient to a value equal to theoretical lift coefficient of the plain flap (corresponding to the region of flow attachment), and a region of less rapid increase (corresponding to a further increase of circulation). Flap-chord ratio had a large effect on the momentum coefficient required to obtain a given lift coefficient with minimum momentum coefficient required in the range of flap-chord ratio greater than 0.30 and less than 0.40.

Vertical location of the blowing flap nose with respect to the nozzle gap was found critical in establishing a successful blowing-flap configuration. Leading-edge devices such as leading-edge droop or a leading-edge slat are necessary on thin wings equipped with blowing flaps if the full lift-coefficient potentialities are to be realized.

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INTRODUCTION

The sustained trend toward higher wing loadings and more restricted landing and take-off attitudes for high-speed airplanes has resulted in the continued need for more powerful aids in the alleviation of the airplane landing and take-off problem. The principal method of solving this problem up to the present has been through the use of single and double slotted flaps on which a large research effort has been expended by the National Advisory Committee for Aeronautics and other research establishments (refs. 1 to 17). The gains in lift realized from the single and double slotted flap have resulted largely through increased wing chord and from the ability of these flap configurations to extend flap effectiveness to deflection angles considerably beyond that obtained on plain flaps. This extension of flap-deflection angle for increased lift of slotted flaps results from the delay of separation over the flaps by means of boundary-layer control resulting from the flow of air through slots actuated by the pressure difference between the lower and upper surface of the wing. Methods of controlling the boundary layer by external means, such as the pumping of jets of air over a wing, have also been investigated and have been proposed for wings with flaps (as early as 1931, ref. 18). The use of such jets has been the subject of a moderate amount of research (refs. 19 to 26). Also considered and investigated has been the removal of boundary layer over flaps by means of suction. (See refs. 26 to 29.)

Although the use of suction and air jets in the region of the flap to provide large lift increments had been established, their use on airplanes had been practically nonexistent, because of the complication of providing or removing the required air quantities. With the advent of the jet engine, which has a large potential for satisfying the air requirements, increased interest and research has centered on flaps utilizing this potential and designated as blowing and suction flaps. The present paper is a correlation of the available data of the various flap-type high-lift devices. The correlation is not intended for design data but mainly to determine the relative merits of the various systems in providing lift, to provide general trends for further research, and to provide sources of available data. Since most of the available data for correlation presented are two dimensional, the correlation is made in the two-dimensional form.

SYMBOLS

Δc_l increment of section lift coefficient

$\Delta c_{l(\alpha=0)}$ increment of section lift coefficient at 0° angle of attack

C_Q	quantity flow coefficient (positive for blowing, negative for suction), $\frac{Q}{VS}$ or $\frac{Q'}{\rho g VS}$
C_μ	momentum coefficient (positive for blowing, negative for suction), $\frac{\rho_j Q V_j}{qS}$
Q	quantity of air, cu ft/sec
Q'	quantity of air, lb/sec
V	free-stream velocity, ft/sec
V_j	jet velocity, ft/sec
S	wing area, sq ft
q	free-stream dynamic pressure, $\frac{1}{2}\rho V^2$, lb/sq ft
ρ	free-stream mass density, slugs/cu ft
ρ_j	jet mass density, slugs/cu ft
g	gravitational constant, 32.2 ft/sec^2
c	wing chord, ft
s	nozzle gap, ft
δ_f	flap deflection with respect to wing chord line, deg
δ_v	vane deflection with respect to wing chord line, deg
c_f/c	flap-chord ratio (fig. 1)
α	angle of attack of wing, deg
c_v/c_f	ratio of vane chord to flap chord (fig. 1)
α_δ	plain-flap effectiveness parameter

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PRESENTATION OF DATA

Most of the available data in the reference reports for suction and blowing flaps use the flow coefficient C_Q as the parameter for defining the effects of air flow. Because of the large differences in nozzle gaps for the various data, the use of the flow coefficient C_Q was unsatisfactory when correlation was attempted of the various blowing-flap data. A more suitable parameter for correlation was the momentum coefficient C_μ. In the present paper and in other unpublished papers it was found that momentum coefficient C_μ was satisfactory for correlation of both high- and low-pressure blowing-flap systems. The data for the high-pressure systems, reference 23 and unpublished data from the Ames Aeronautical Laboratory, were obtained directly in the form of momentum coefficient. Generally the remainder of the available blowing-flap data was from low-pressure systems presented in the form of flow coefficients C_Q. These data have been converted to momentum coefficients by the following relationships derived and used in references 26 and 30.

$$C_\mu = 2C_Q \frac{V_j}{V} = 2\left(\frac{c}{s}\right)C_Q^2$$

Negative values for C_μ represent the suction conditions. The relationships are believed satisfactory for the low-pressure data because nozzle coefficients for shapes similar to that used in the airfoils approach unity. Any errors that might arise are believed to be small and will have no appreciable effect on the general trend of the data. It is also realized that correlation of data from many different sources is generally subject to some inaccuracies; however, it is believed that the general trends are valid.

Unpublished suction-flap and blowing-flap data obtained from tests at the Ames Aeronautical Laboratory were not obtained directly at zero angle of attack because separation existed on the wing leading edge and the tunnel walls for this condition, and variations occurred in the lift-curve slope. The values used in the present paper were obtained by using the difference between the lift coefficient for flap deflected and undeflected obtained at -4° angle of attack (where separation was minimized). These values are believed representative of the lift coefficient that would be obtained at zero angle of attack if separation on the wing leading edge and the tunnel walls was absent at this angle. Blowing-flap data, as for example reference 25, generally show about a constant lift-coefficient increment for a given flap deflection throughout the angle-of-attack range similar to that usually found for plain and slotted flap without blowing. The data for the 0.28c flap, reference 22, were obtained by extrapolation of data at moderate angles of attack to zero.

In the present paper the flap-chord value may be different from the value given in the reference data. This results from lack of uniformity in defining flap chord in the available reference data. In order to unify the definition of flap-chord ratio, in the present paper, flap chords for suction or blowing flaps are generally defined as the distance from the nozzle lip to the wing trailing edge, and wing chord is the summation of this length and the distance from the wing leading edge to the lip (fig. 1). In order to remove the effect of chord-extension for correlation purposes, lift coefficients, flow coefficients, and momentum coefficients in these instances have been adjusted for the increase of wing area. In general, these corrections were small. The chord for single slotted flaps has been defined as the distance from flap leading edge to wing trailing edge and the chord for double slotted flaps as the distance from the vane leading edge to the wing trailing edge (see fig. 1). The chord-extension effect has not been eliminated from the single- and double-slotted-flap data. It is believed that for the zero-angle-of-attack case considered, chord-extensions will have a relatively small effect on the general comparison of the lift capabilities of the various flap arrangements considered in the present report.

A comparison of the lift capabilities of plain, single slotted, double slotted, suction, and blowing flaps as obtained from the reference reports for various chords is presented in figure 2. Data for the 0.25c-plain-flap configuration of figure 2(b) were obtained by interpolation of 0.20c- and 0.30c-plain-flap data of reference 31. The 0.40c-plain-flap data of figure 2(d) were obtained from reference 32.

A comparison of the effect of jet and suction systems on a wing with flap is presented in figure 3. The effect of vane size on the two-dimensional lift capabilities of double slotted flaps of approximately 25 percent chord is presented in figure 4. In figure 5 is presented the effect of momentum coefficient C_μ on the lift-coefficient increment available at zero angle of attack for blowing flaps of various chords at several flap deflections. Figure 6 presents the effect of jet reaction in the vertical direction on the variation of lift coefficient with momentum coefficient. The effect of momentum coefficient on the variation of lift-coefficient increment of a plain wing at several angles of attack is presented in figure 7. The minimum momentum coefficient required to obtain a given lift coefficient for blowing-flap configurations of various chords is given in figure 8. The effect of jet location on the lift increment available for a blowing flap is shown in figure 9. The effect of wing thickness and the use of a leading-edge slat to delay leading-edge separation is shown in figure 10. The effect of jet slot width throughout the C_μ range is also shown in figure 10.

DISCUSSION

Comparison of Various Flap Configurations

The comparison of the lift capabilities of the various types of flap at angles of attack equal to zero is given for flaps of several chord ratios in figure 2. The slotted-flap configurations were capable of extending the nearly linear variation of lift coefficient with deflection to higher values. For example, among the flaps with c_f/c of 0.25 (fig. 2(b)), the plain flap had a nearly linear range to 10°, the single slotted flap increased the nearly linear range to about 35°, and the addition of a suitable vane ahead of the flap (double slotted flap) extended the deflection for nearly linear variation of Δc_l with δ_f to about 60°. Although the slotted flaps extend the range of δ_f, the lift-coefficient increments obtained fell below the theoretical values for a plain flap

$$\Delta c_l = \frac{2\pi\alpha_\delta\delta}{57.3}$$

In order to obtain or exceed the theoretical values, some type of forced boundary-layer control is required. From the data available, it should be possible to obtain lift coefficients up to theoretical values by the use of suction through a slot (refs. 26 to 28) or by area suction (ref. 29). Values greater than theoretical up to at least $\delta_f = 60^{\circ}$ (figs. 2(a) and 2(d)) can be obtained by applying boundary-layer control in the form of a high-speed jet blowing over the deflected flap.

The discussion in this report, in general, will be concerned with the effects of the variables on the lift-coefficient increment at zero angle of attack. It is realized that the final selection of a flap would of necessity consider weight, mechanical complexity, lift-drag ratio for both take-off and landing, and so forth. The variables, in general, are a function of wing plan form and airplane configuration. If a given lift-coefficient increment is required that is below theoretical, considerable choice in device is available, and if the value is near theoretical, either a suction or blowing flap can be used. However, if the lift coefficient required is above theoretical, then (from the data available) recourse must be made to the blowing type of flap. These concepts are also indicated by the data of figure 3. However, it should be noted that the various configurations shown in figure 3 are not necessarily optimum. For example, it is expected that the use of area suction would result in a much more rapid increase toward theoretical lift coefficient than that shown for suction through a slot.

Slotted Flaps

The ability of the slotted flap to increase the available lift coefficient over the plain flap is the result of both the extension of the wing area and the induced boundary-layer control over the flap caused by flow through the slots at the flap leading edge. The data shown for the slotted flaps have been obtained from investigations where, in general, the objective was high maximum lift coefficient and therefore the lift increment at zero angle of attack may not be the optimum. However, the data are believed to be representative of the range of lift-coefficient increment that can be obtained.

The ability of a double slotted flap to provide lift is a function of the size of the vane ahead of the flap. Increasing the vane-flap ratio (fig. 4) from 0 to 0.46 increased the largest obtainable increment in lift coefficient at zero angle of attack $\Delta C_{l_{(\alpha=0)}}$ from 1.65 to about 2.8. Part of this increase can be attributed to an effective increase in flap chord; however, most of the increase resulted from the increased flap angle $\left(30^\circ \text{ for } c_f'/c = 0 \text{ to } 70^\circ \text{ for } c_f'/c = 0.46\right)$. The deflection of the vane also increases as c_v/c_f' increases for maximum effectiveness. Similar trends were obtained in the three-dimensional data of reference 17. Since there are several papers (refs. 15 and 16, for example) dealing with slotted flaps as high-lift devices, no further discussion of the effects of flap chord, vane chord, or their arrangement will be made. It is felt that the trends of figure 4 will hold for other flap-chord ratios and indicate that, although the flap deflection and lift increment can be increased by increases in c_v/c_f', the value of $\Delta C_{l_{(\alpha=0)}}$ will still fall short of the theoretical value for a plain flap.

Boundary-Layer Flap Suction

The discussion of suction flaps must be more brief than that of either slotted flaps or blowing flaps since there are so few systematic data available (refs. 26 to 29). The results (figs. 2 and 3, and ref. 29) do indicate, however, that with an efficient suction flap, lift increments approaching or equaling the theoretical value can be obtained. As mentioned previously, the configurations shown in figure 3 are not necessarily optimum configurations, especially for the suction flap. The results of reference 29 indicate that one of the more efficient arrangements would use a porous surface (area suction) rather than a slot to remove the boundary layer and prevent separation over the flap.

Boundary-Layer Flap Blowing

A consistent variation of $\Delta C_{l_{(\alpha=0)}}$ is shown with both momentum coefficient C_μ and flap-chord ratio c_f/c (fig. 5) when the data are compared at constant flap angle. These trends are apparent despite relatively large variations existing in thickness, pressure ratio, and gap size. It will be shown that these are secondary effects when the data are compared using momentum coefficient and when the wing is equipped with leading-edge devices.

Throughout the flap-chord ratio and flap-deflection range, an increase in lift coefficient occurred with an increase in momentum coefficient. The lift-coefficient increase was most rapid up to the theoretical value for plain flaps on thin wings. This region is believed to correspond to the condition where the primary effect of the blowing air is to bring about reattachment of the separated flow. Beyond this region of reattachment of flow, the rate of increase of $\Delta C_{l_{(\alpha=0)}}$ with C_μ was lower. The decreased rate of change of $\Delta C_{l_{(\alpha=0)}}$ with C_μ corresponded approximately to the rate obtained on a plain wing at zero angle of attack altered by consideration of the vertical change in momentum (fig. 6) resulting from downward deflection of the jet stream by the flap (Coanda effect; refs. 33 and 34). Similar regions of flows were noted in the analysis of reference 30.

As shown by the data correlated in figure 5, the increase of lift coefficient with momentum coefficient was generally more rapid at the larger flap-chord ratios up to 0.32c; above this at 0.43c, there was a reduction in the rate of increase of lift coefficient with momentum coefficient.

Although the amount of data available is small, particularly for the large values of δ_f, the trends are generally similar throughout the flap-deflection range. For a given flap-chord ratio the value of C_μ required to obtain the theoretical $\Delta C_{l_{(\alpha=0)}}$ increased as δ_f increased. For example, C_μ for theoretical $\Delta C_{l_{(\alpha=0)}}$ was 0.052, 0.126, and 0.161 for δ_f of 20°, 45°, and 53° of a 0.25c flap. This increase with δ_f is to be expected considering the larger effort required to reattach the flow over the flap as δ_f increases.

An analogous situation occurred with the use of a jet of air over a plain wing $\left(\delta_f = 0, \text{ fig. } 7\right)$. As angle of attack increased, the momentum coefficient required to obtain theoretical lift coefficient also increased.

For a given momentum coefficient, larger lift coefficients were obtained as the angle of attack increased up to 15° (near the stall angle for the plain wing). For angles of attack of 20° and higher, less increase of lift coefficient for the plain wing was obtained with increased momentum coefficient. At 25° angle of attack, the increase of lift with momentum coefficient was less than that obtained at zero angle of attack for the momentum-coefficient range investigated.

The desirable arrangement of any high-lift device is the one that gives the most lift with the least penalty. In the case of slotted flaps, this arrangement is the lightest and simplest configuration that will give the desired lift and drag. In the case of the blowing flap it is the one that requires the least power or in most cases of current interest the arrangement that requires minimum C_Q (because of minimum engine air bleed requirement). As discussed previously, the most suitable parameter for correlation of the available data was the momentum coefficient. Since the momentum coefficient is an indication of the power required or for fixed nozzle gap size the flow coefficient required, the data of figure 5 have been cross-plotted in figure 8 to show the value of C_μ required to obtain a given lift coefficient as a function of c_f/c. The data for $c_f/c = 0$ were obtained by extrapolating the plain-wing data (fig. 7) considerably beyond the range of the investigation. Some extrapolation was necessary for the other data but of considerably smaller magnitude than for the plain-wing data.

The variation of c_f/c with C_μ indicates that a given lift coefficient can be obtained with the least C_μ for flap-chord ratios of the order of 0.35.

Effect of Blowing-Flap Position

In addition to the effects of flap-chord ratio and flap deflection, the position of the flap nose relative to the jet is of major importance. Examination of the data of reference 26 and figure 9 (ref. 23) indicates that the vertical location of the flap with respect to the jet axis is an important criterion in establishing a successful blowing flap. It appears that the jet must impinge upon the flap (fig. 9) or be ejected along its surface (fig. 2(c)) if the rapid increase in $\Delta C_{l_{(\alpha=0)}}$ with C_μ is to be obtained. There appears to be some tolerance allowed in the longitudinal position of the jet with respect to the flap nose (fig. 9). This is also indicated in a comparison of Ames unpublished data and the data of reference 23 in figure 2(c) and also in figures 5(b) and 5(d), where the data for both flap configurations correlate closely when consideration is made of flap-chord effects. In the Ames investigation the air was ejected near the flap peak pressure and in the investigation of reference 23 the air was ejected ahead of the flap nose. It appears, therefore, that if the jet of air is located in a satisfactory position relative to the flap, there is generally little difference between a plain and slotted flap as far as lift effectiveness is concerned.

Effect of Wing Thickness

Although there are not sufficient data to establish any variation of $\Delta C_{l_{(\alpha=0)}}$ with t/c for blowing flaps, the data do indicate that the value of $\Delta C_{l_{(\alpha=0)}}$ was larger for thicker airfoil sections (fig. 10). The data $\left(C_\mu = 0.16\right)$ indicate that the large loss associated with thinner airfoils is alleviated somewhat by the addition of a leading-edge device. It would appear, therefore, that if full lift potentialities of the thinner sections are to be realized, some sort of leading-edge device to prevent leading-edge separation will be necessary.

Effect of Slot Width

Using the momentum coefficient as a basis for correlation, the negligible effect of slot width on the obtainable lift coefficient for a low-pressure system is shown by the data of reference 21 (fig. 11). Although these data for conversion to momentum coefficient were obtained at 10° angle of attack, the results are typical of other unpublished data at zero angle of attack.

General Remarks

A correlation has been made of the limited two-dimensional data available on blowing-, suction-, slotted-, and plain-flap high-lift devices. The correlation has been restricted mainly to the available lift coefficient at zero angle of attack. Selection of a suitable high-lift device for achieving similar increases in the maximum lift coefficient for an airplane configuration would also have to consider other factors which are beyond the scope of the present paper, such as longitudinal trim requirements, lift-drag ratios, angle-of-attack effects, power requirements for air supply, and structural complications.

CONCLUSIONS

A correlation of the available two-dimensional data of various flap-type high-lift devices has indicated the following general conclusions:

1. For a given flap-chord ratio, the largest increments of lift coefficient at zero angle of attack were obtained for the blowing flaps. Next and in the order of decreasing ability to provide lift coefficient were the suction flap, the double slotted flap, the slotted flap, and the plain flap.

2. The ability of a double slotted flap to provide lift was found to be closely related to the size of the vane ahead of the flap. For example, progressively increasing the vane-flap ratio from 0 to about 0.46 for a 0.25-chord flap increased the obtainable increment of lift coefficient at zero angle of attack from 1.6 to about 2.8 almost linearly.

3. Good agreement was obtained between the available blowing-flap data when momentum coefficient was used as the parameter for correlation.

4. Lift coefficient for the blowing flap, when presented as a function of momentum coefficient, generally extended through two regions: an initial rapid increase to plain-flap theoretical lift coefficient (corresponding to the region of flow attachment) and then a less rapid increase (corresponding to a further increase of circulation).

5. Flap-chord ratio had a large effect on the momentum coefficient required to obtain a given lift coefficient, with minimum momentum coefficient required in a flap-chord-ratio range greater than 0.30 and less than 0.40.

6. Vertical location of the flap nose with respect to the nozzle axis is critical in establishing a successful blowing-flap configuration.

7. Leading-edge devices such as leading-edge droop or a leading-edge slot are necessary on thin wings equipped with blowing flaps if the full lift potentialities are to be realized.

Langley Aeronautical Laboratory,
National Advisory Committee for Aeronautics,
Langley Field, Va., April 15, 1955.

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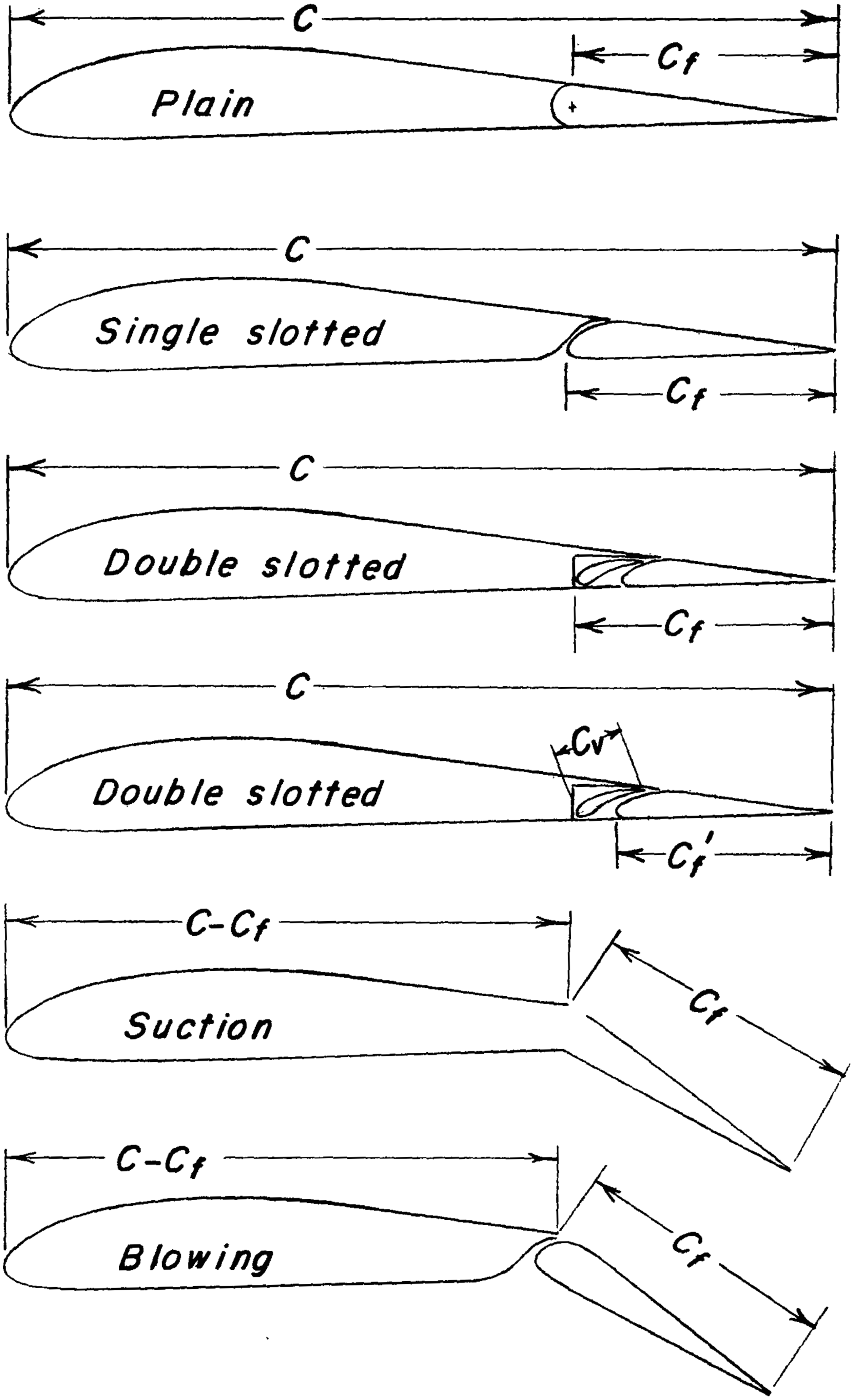
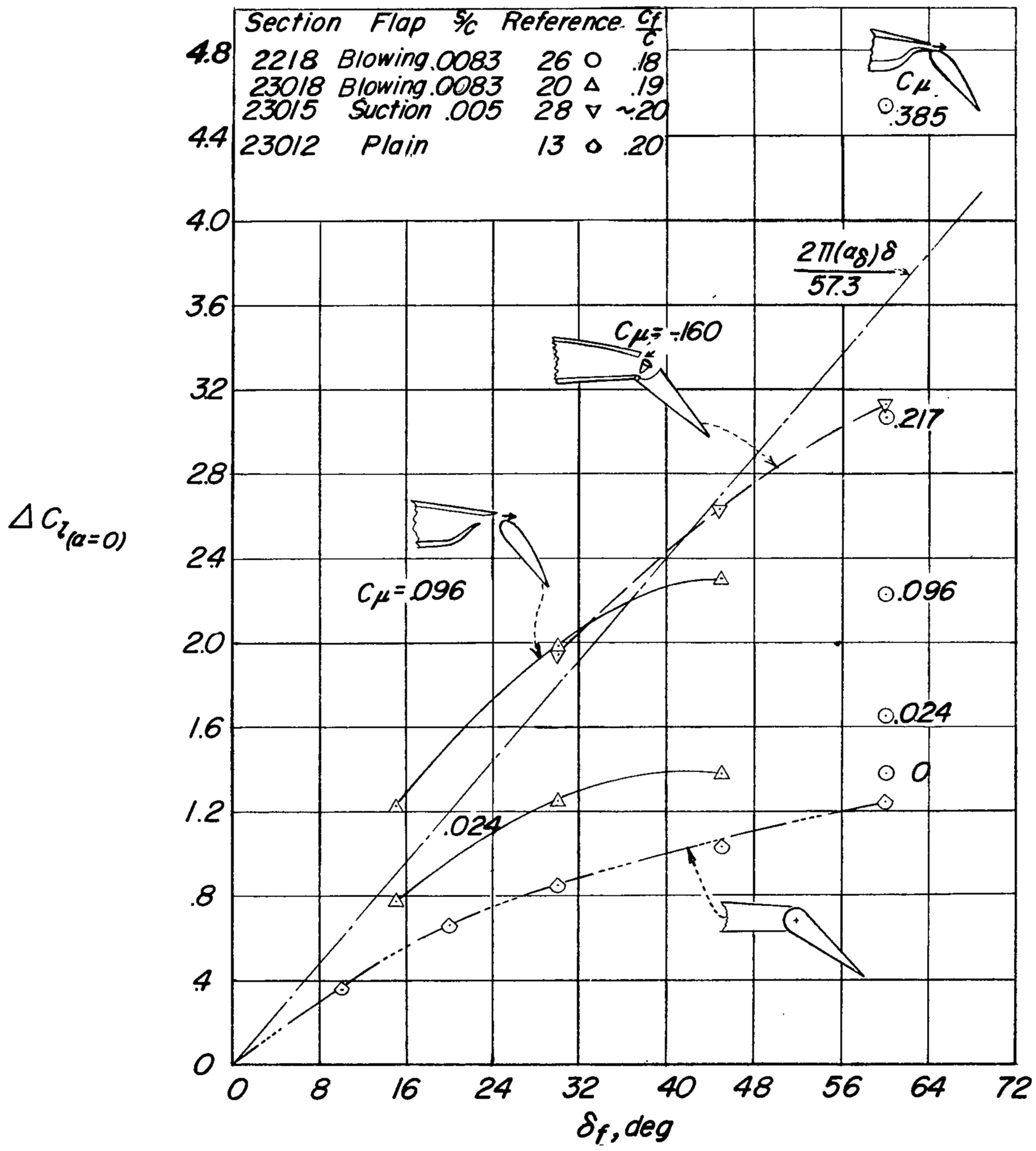
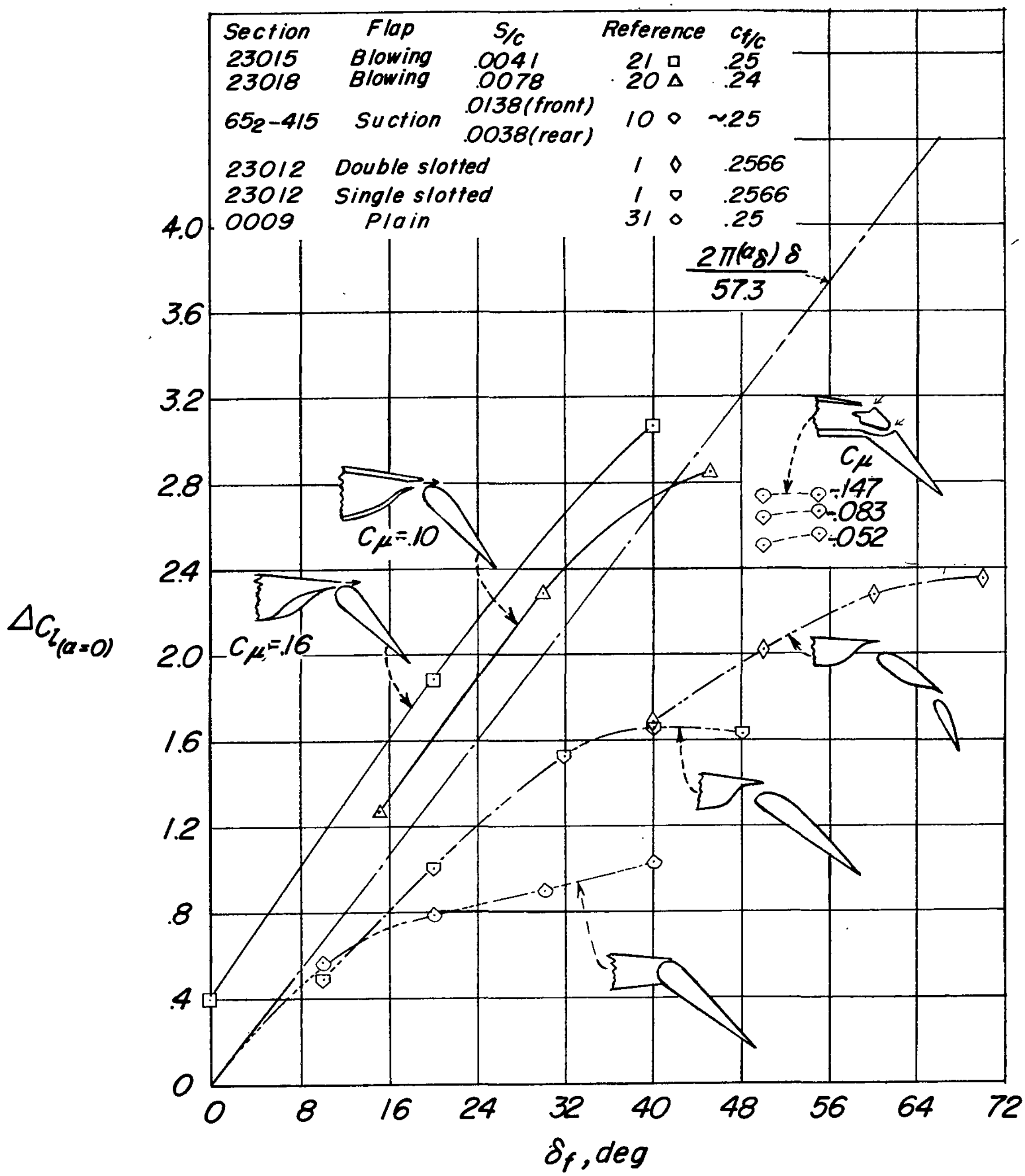


Figure 1.- Definition of flap chord.



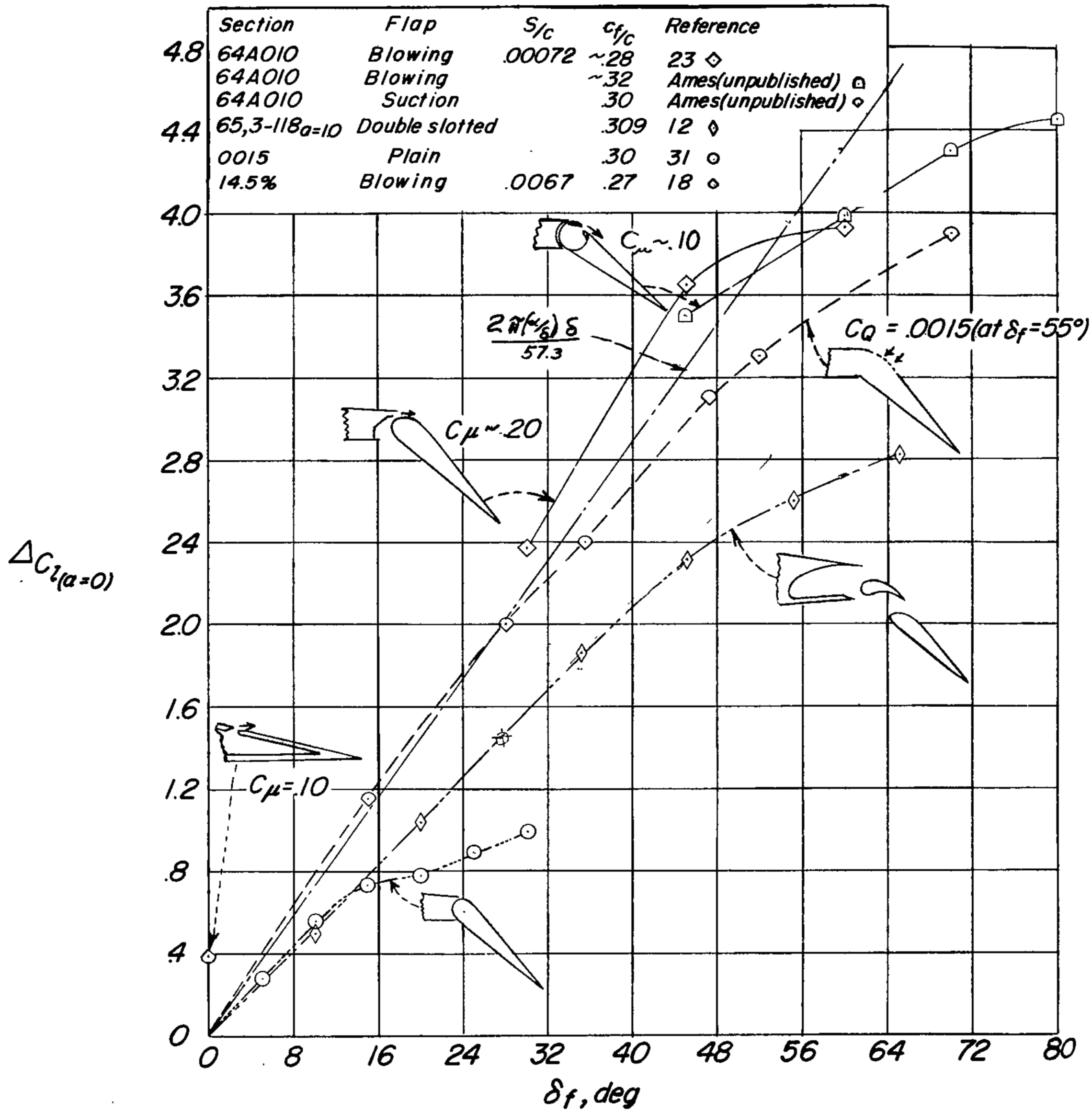
(a) $c_f/c \approx 0.20$.

Figure 2.- General comparison of lift-coefficient increment available from blowing, suction, slotted, and plain flaps of various chords in two-dimensional flow.



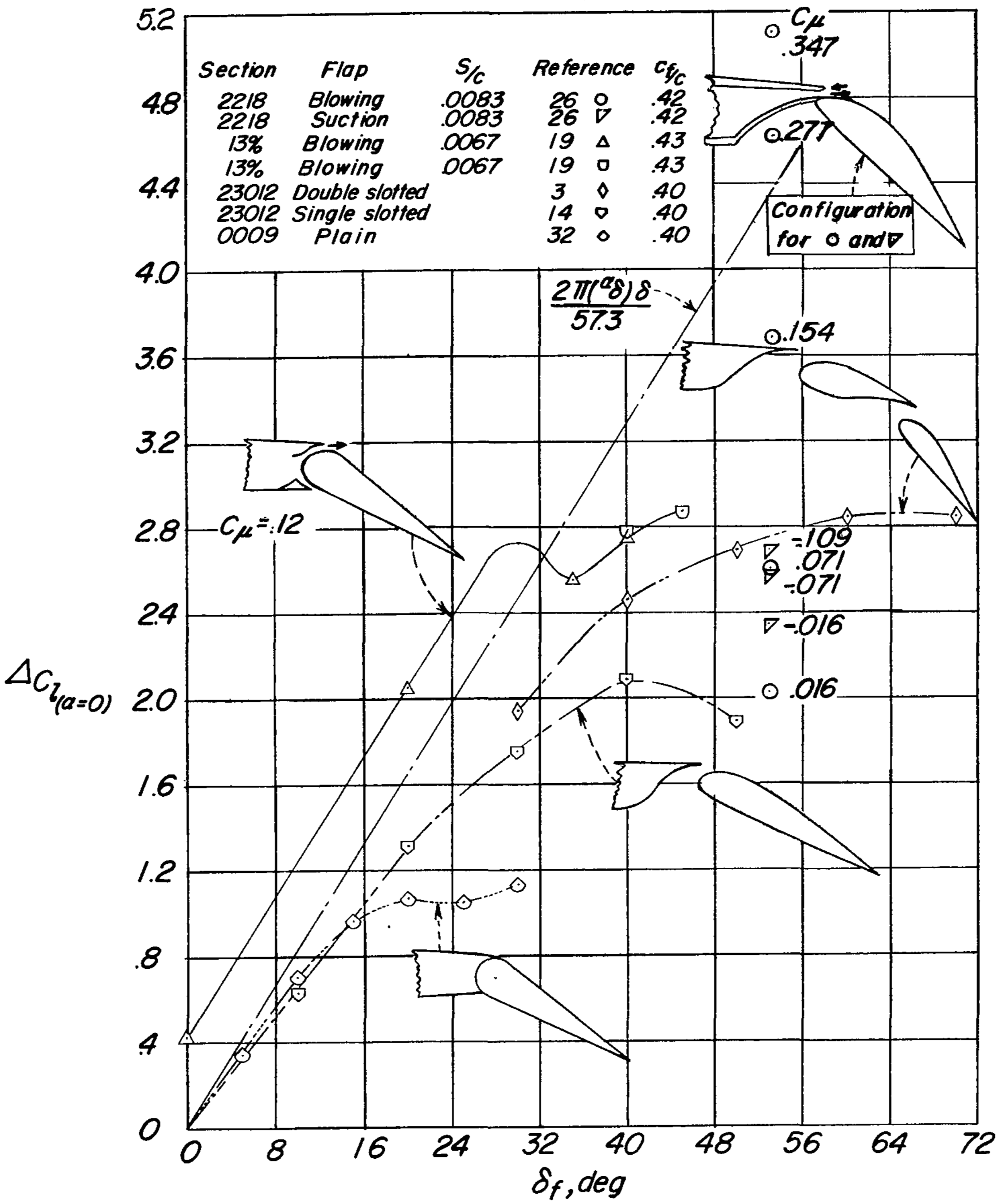
(b) $c_f/c \approx 0.25$.

Figure 2.- Continued.



(c) $c_f/c \approx 0.30$.

Figure 2.- Continued.



(d) $c_f/c \approx 0.40$.

Figure 2.- Concluded.

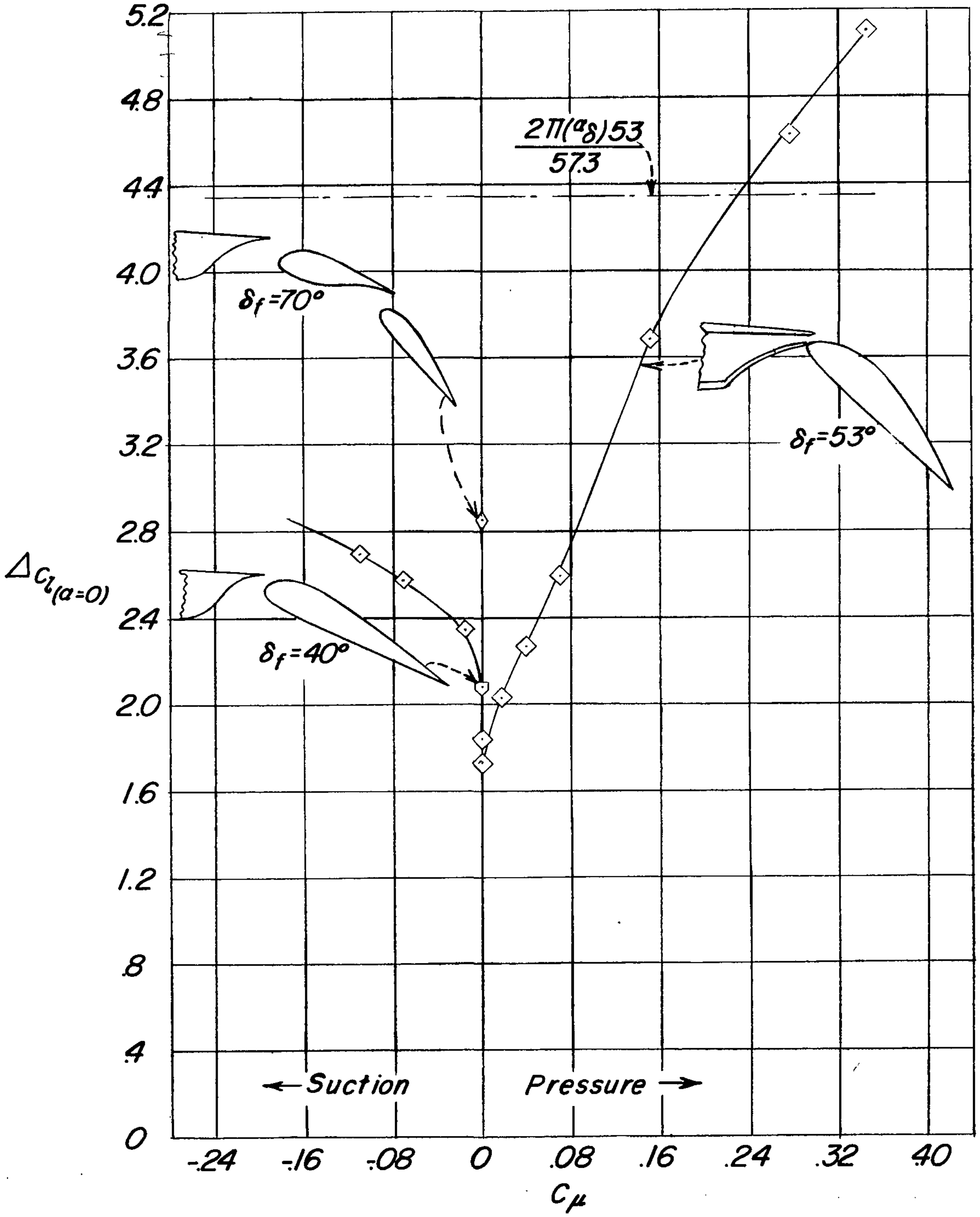


Figure 3.- Comparison of lift-coefficient increment available at various momentum coefficients for suction and blowing flaps with single and double slotted flaps. $c_f \approx 0.40c$.

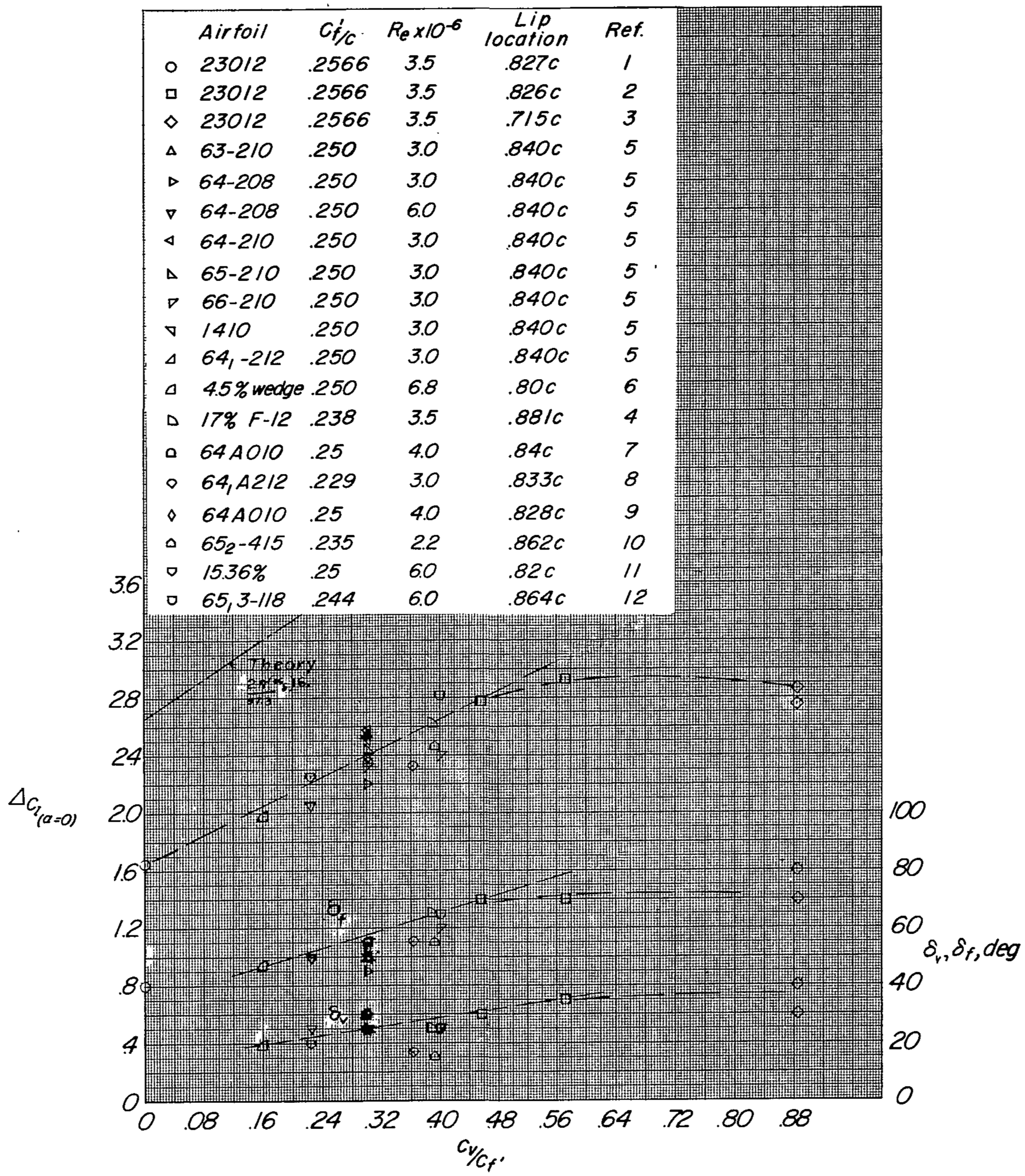
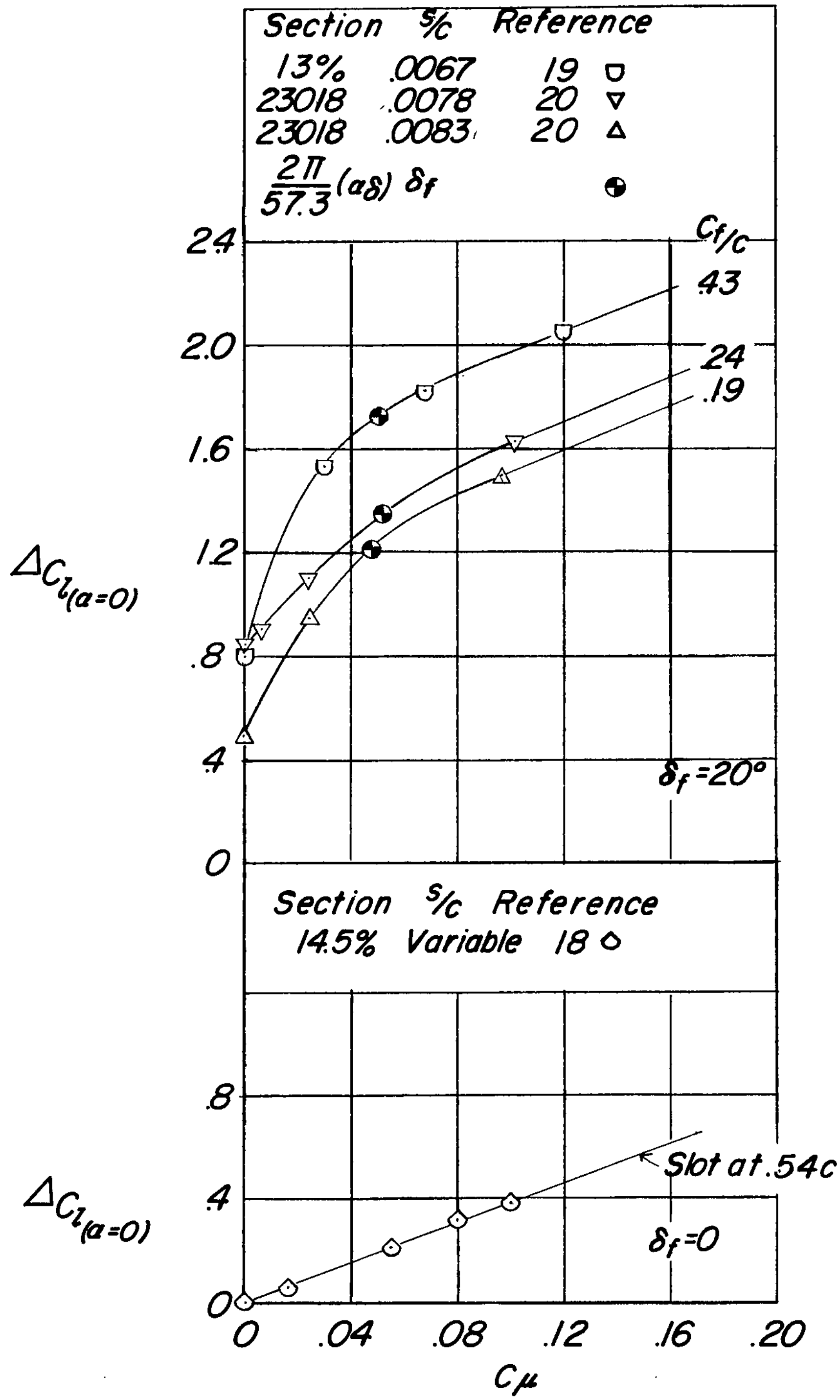
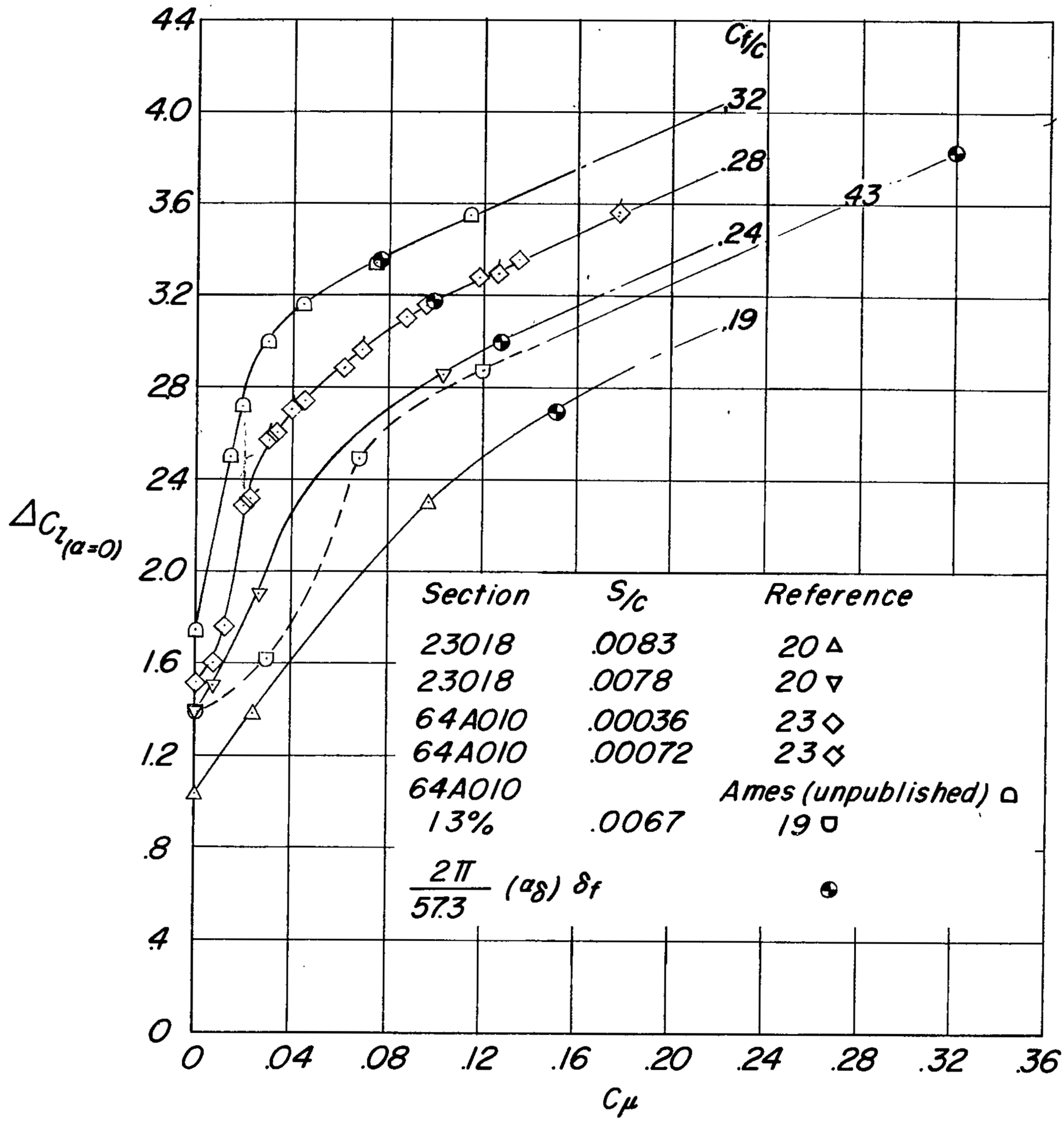


Figure 4.- Effect of vane size on the two-dimensional lift capabilities of a double slotted flap (rear flap chord constant 0.25c).



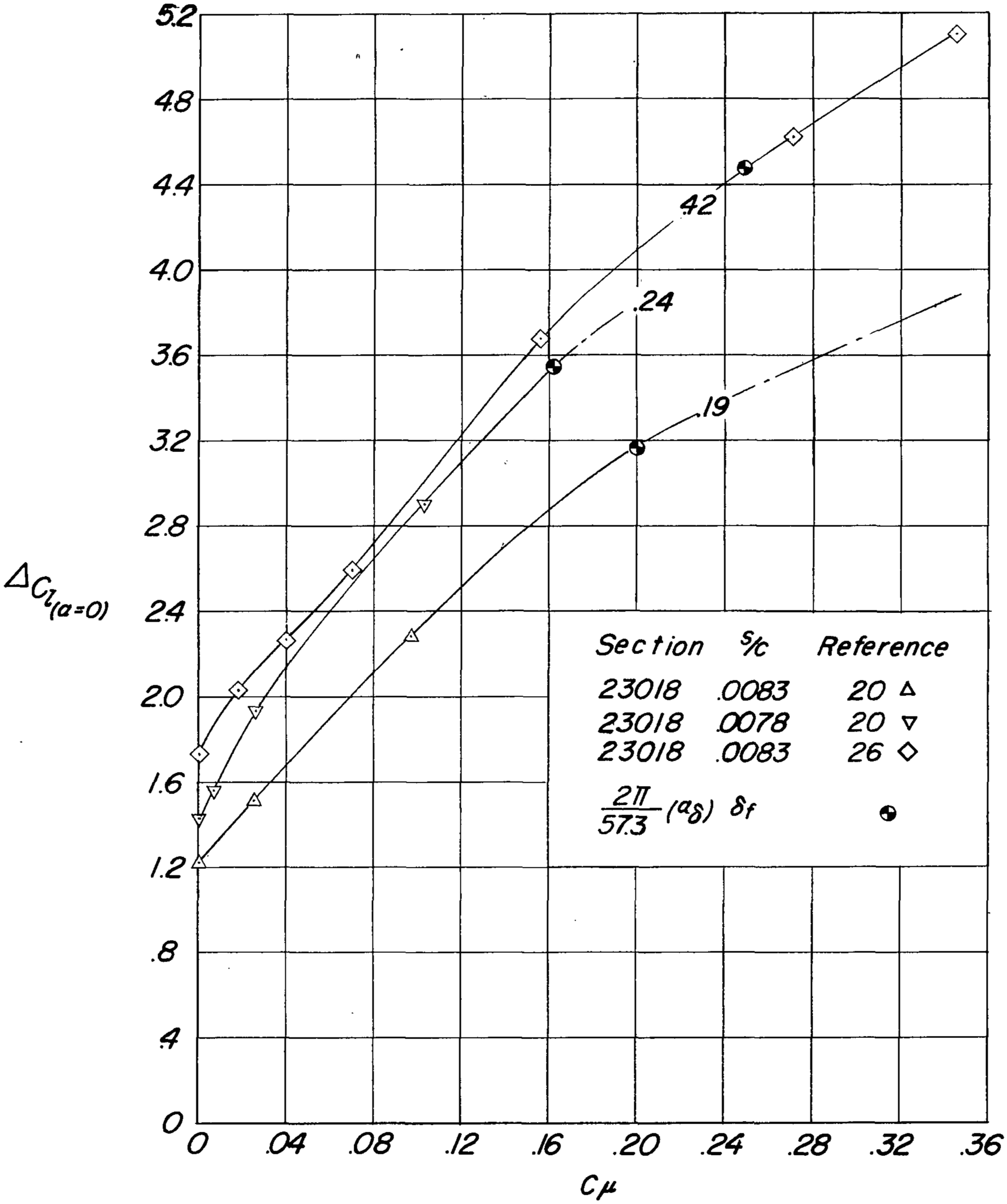
(a) $\delta_f = 0^o$ and 20^o.

Figure 5.- Effect of momentum coefficients for blowing flaps of various chords.



(b) $\delta_f = 45^\circ$.

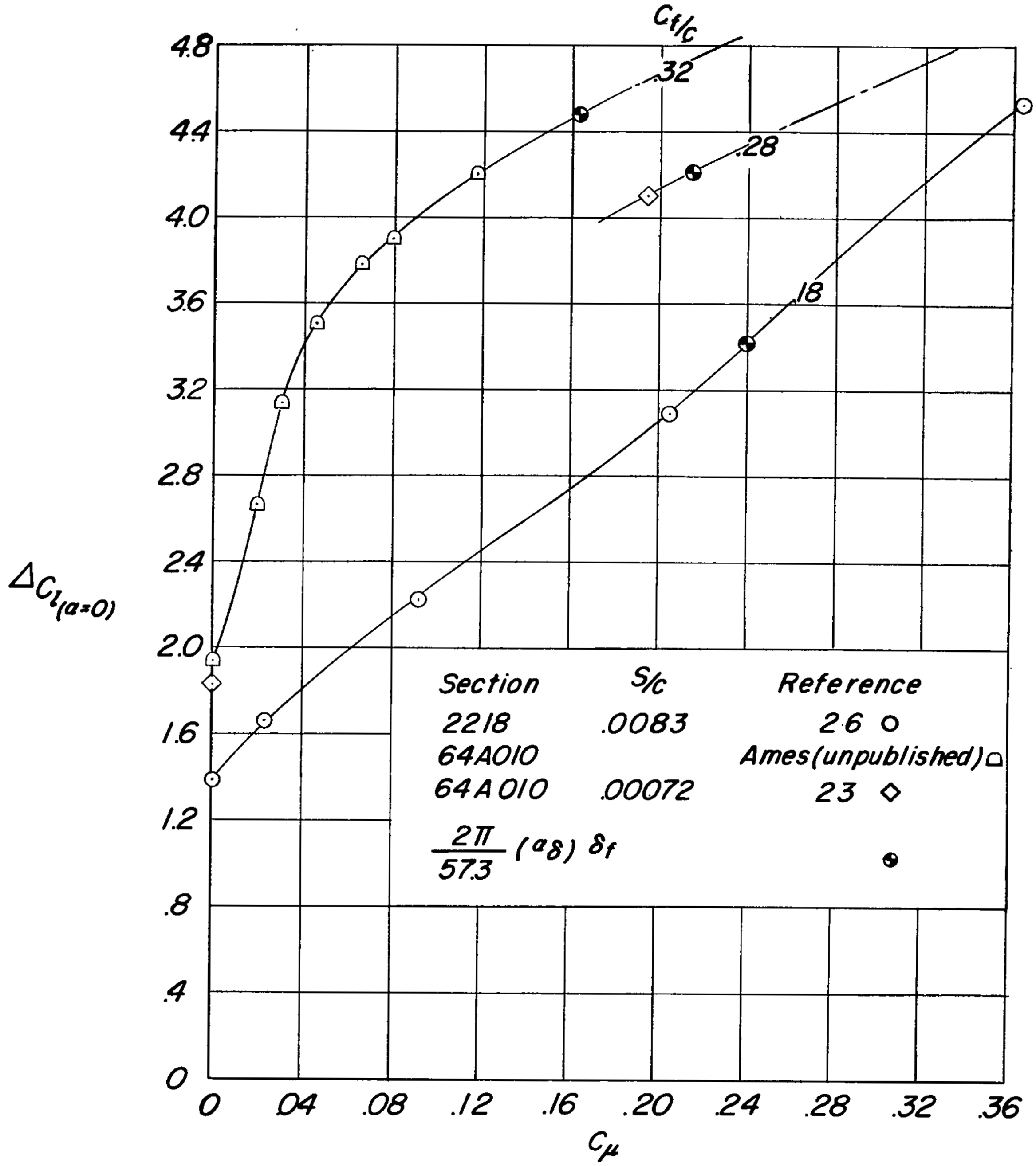
Figure 5.- Continued.



(c) $\delta_f = 53^\circ$.

Figure 5.- Continued.

[redacted]



(d) $\delta_f = 60^\circ$.

Figure 5.- Concluded.

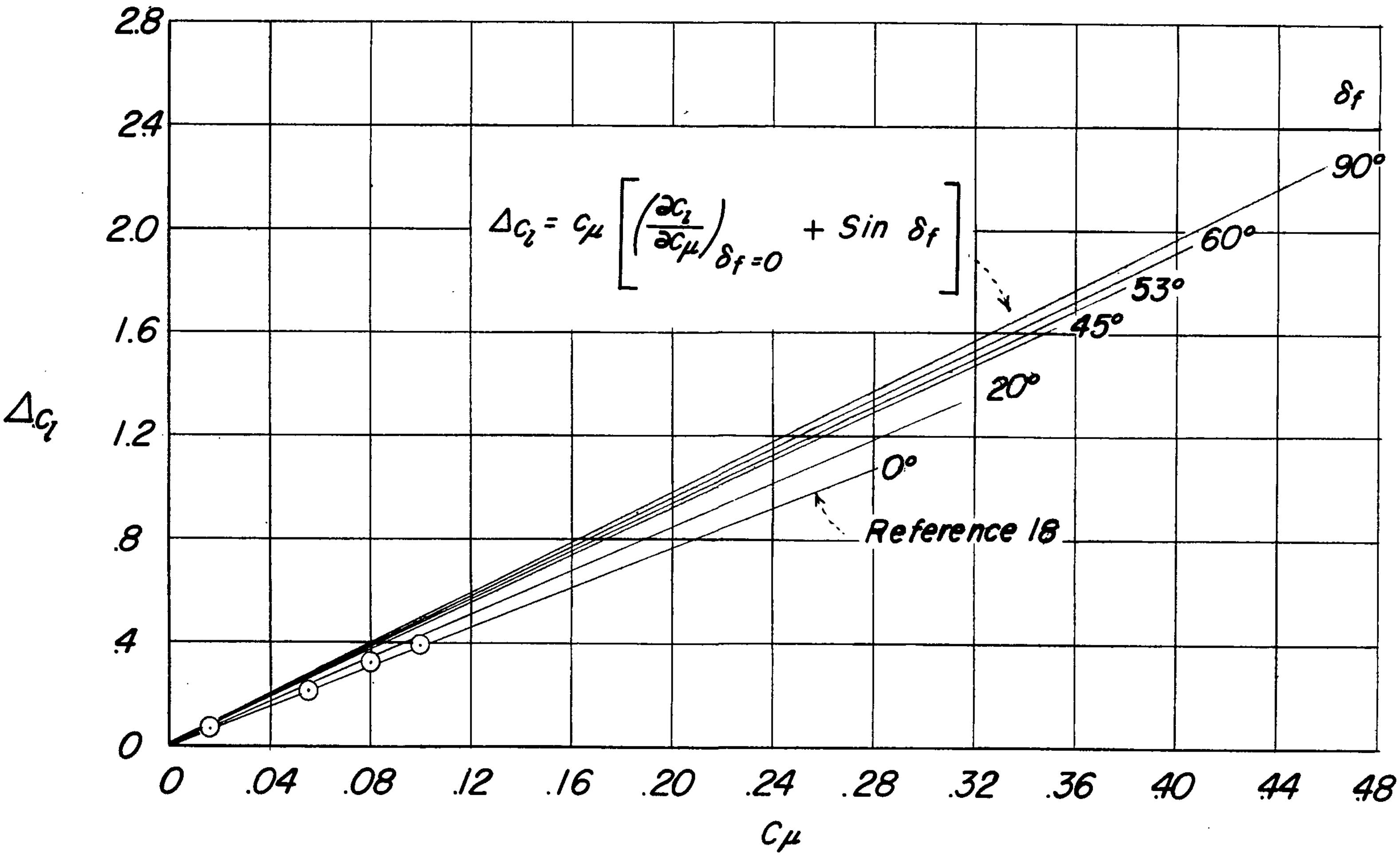


Figure 6.- Variation of Δc_l with C_μ for a plain wing (jet at 0.539c) with consideration of the effect of jet reaction in the vertical direction resulting from downward deflection of the jet stream through various angles.

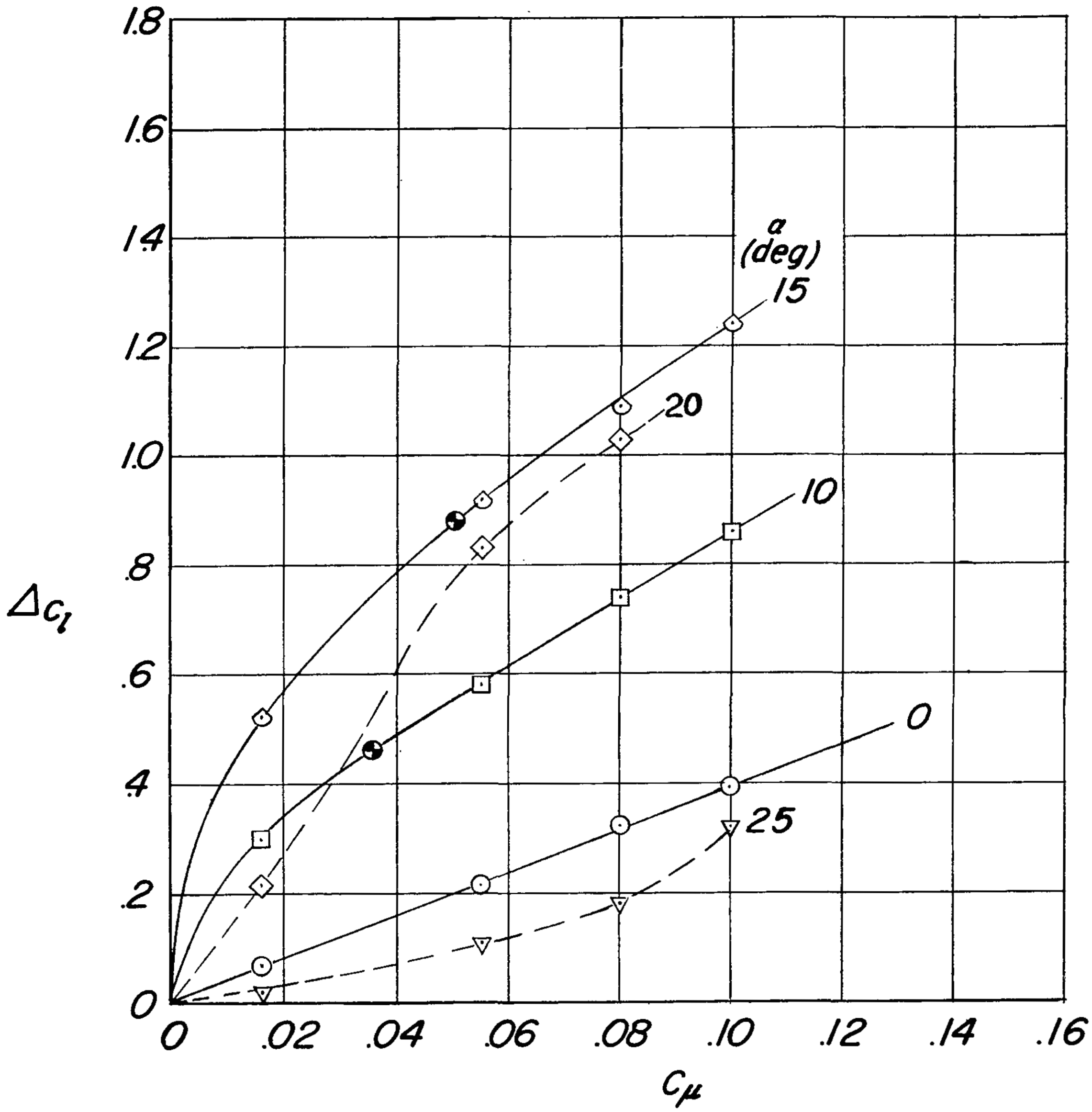


Figure 7.- Effect of angle of attack on the variation of lift coefficient with momentum coefficient for a wing with $\delta_f = 0$. Slot at 0.539c (ref. 18).

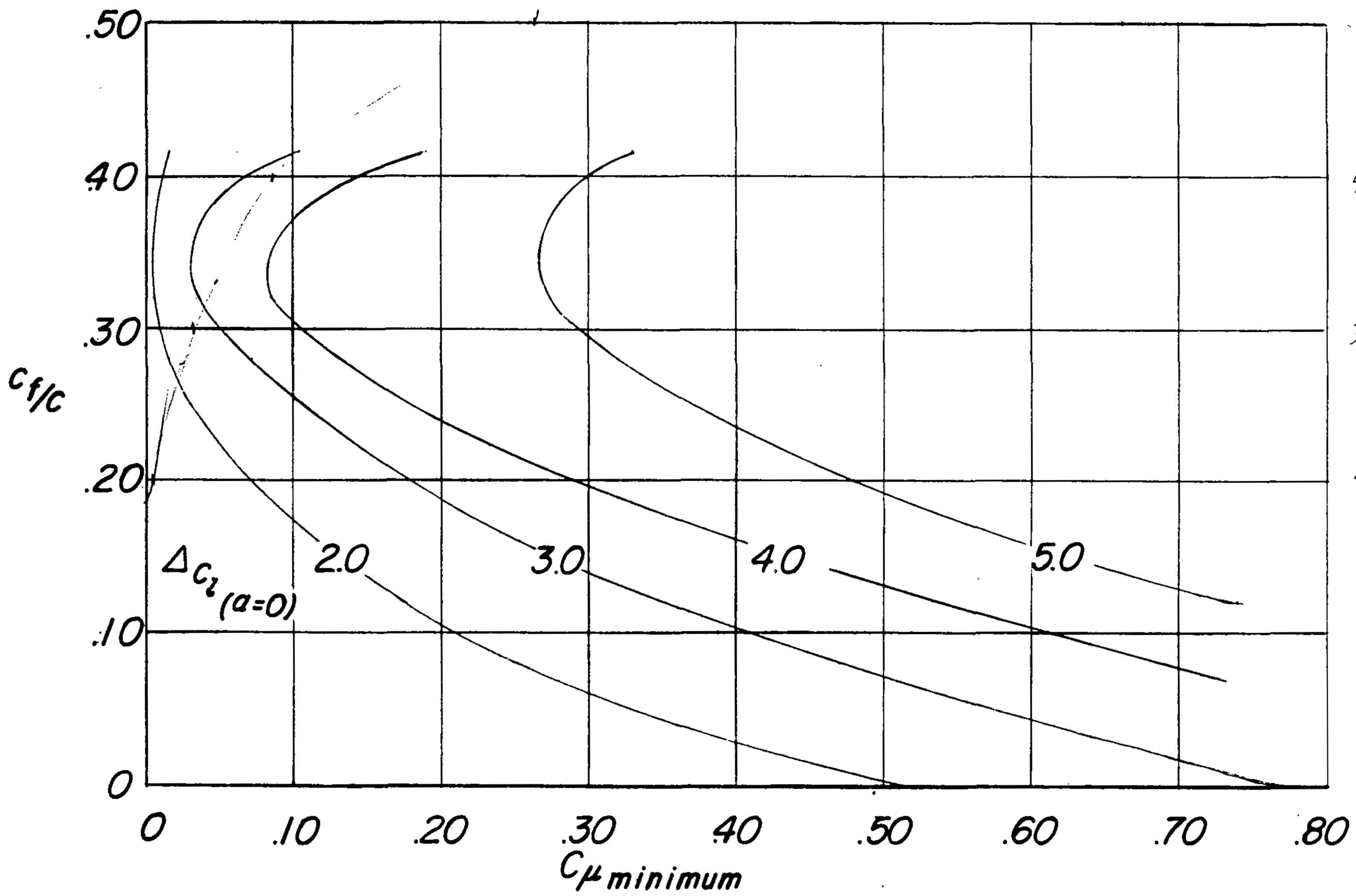


Figure 8.- Minimum momentum coefficient required to obtain a given lift coefficient for blowing-flap configurations as determined from figure 5.

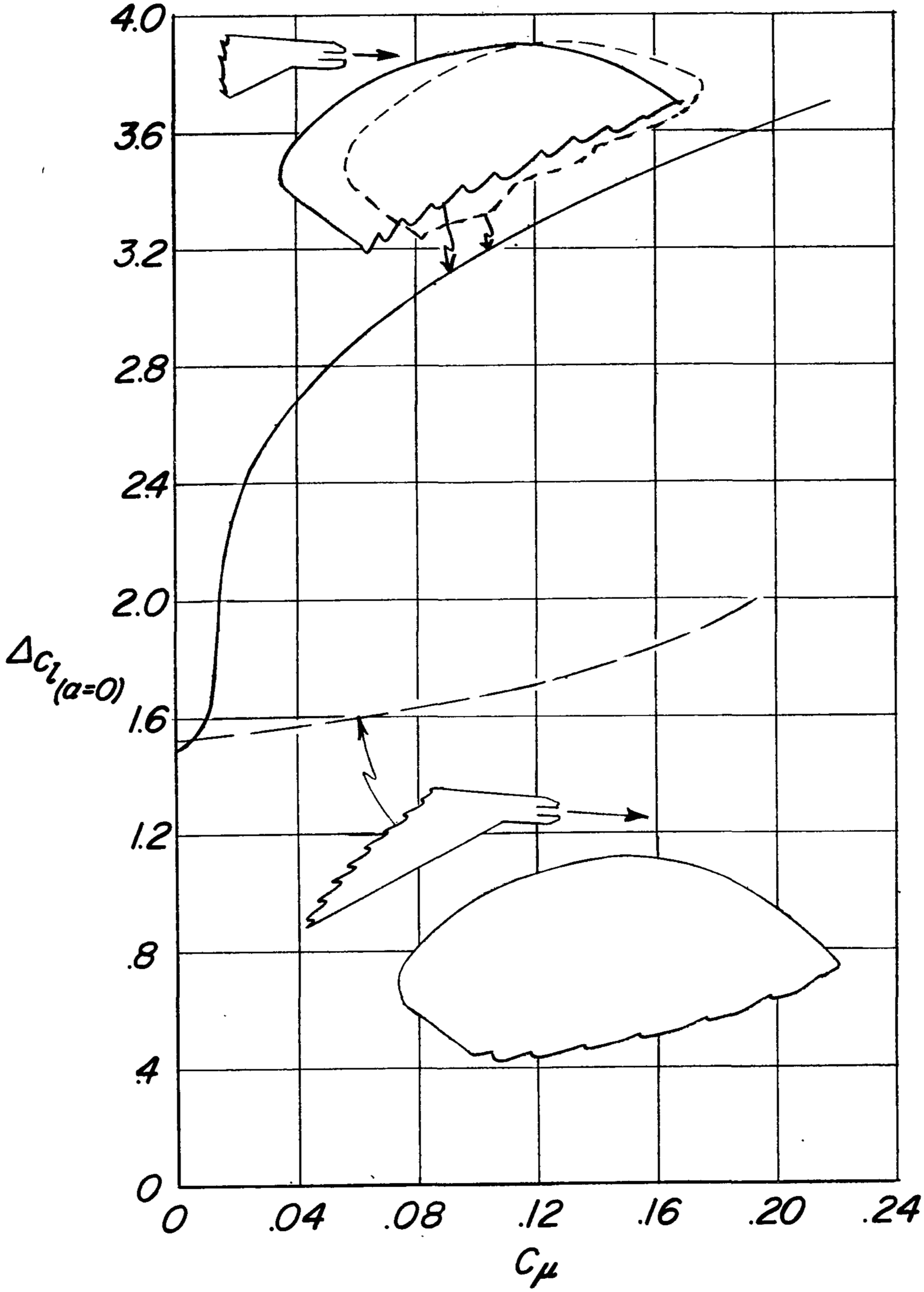


Figure 9.- Effect of jet location $\delta_f = 45^\circ$ (ref. 23).

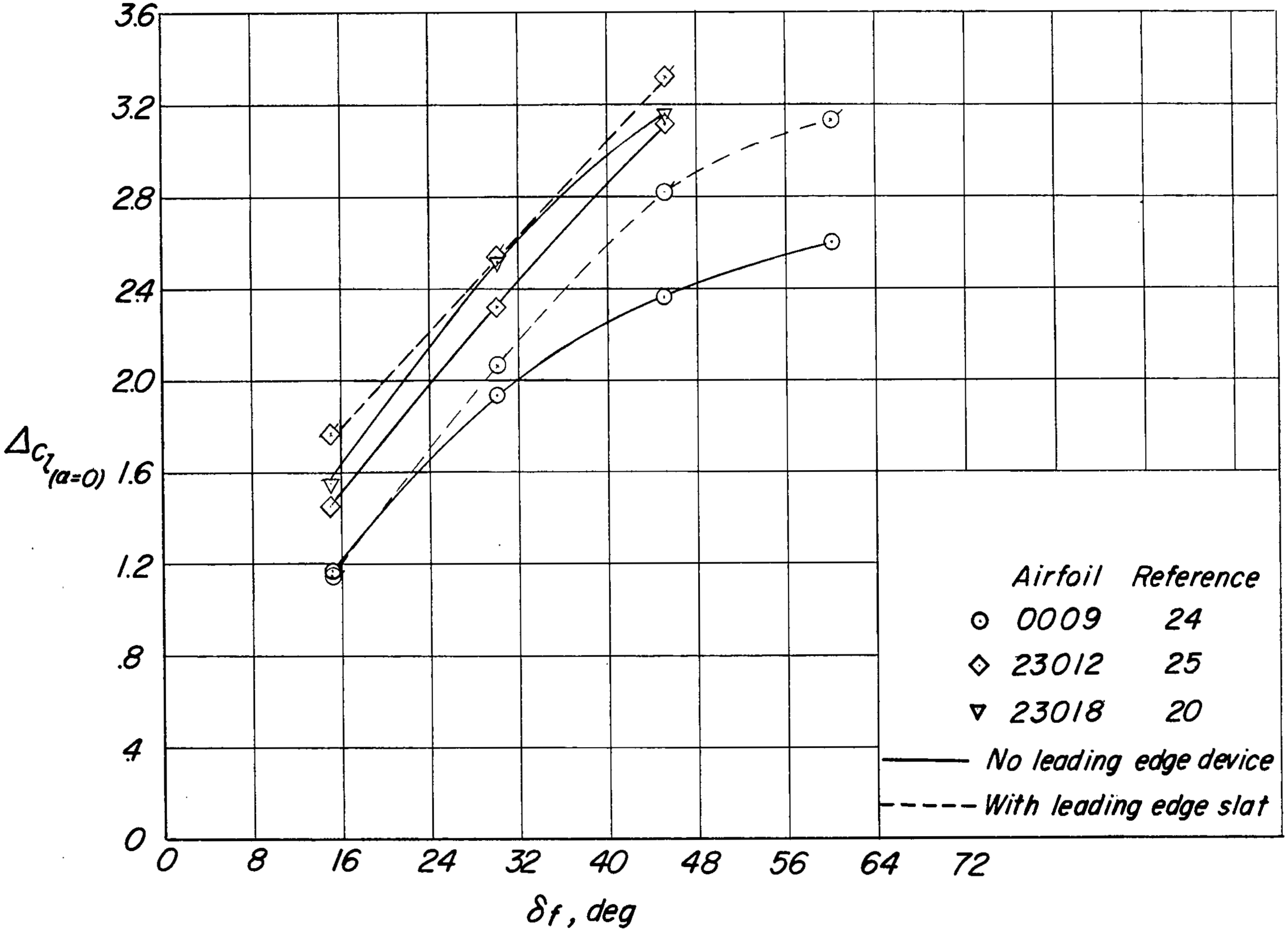


Figure 10.- Effect of wing thickness and leading-edge slat on the lift increment available for blowing flaps of approximately 0.25c. $C_{\mu} = 0.16$.

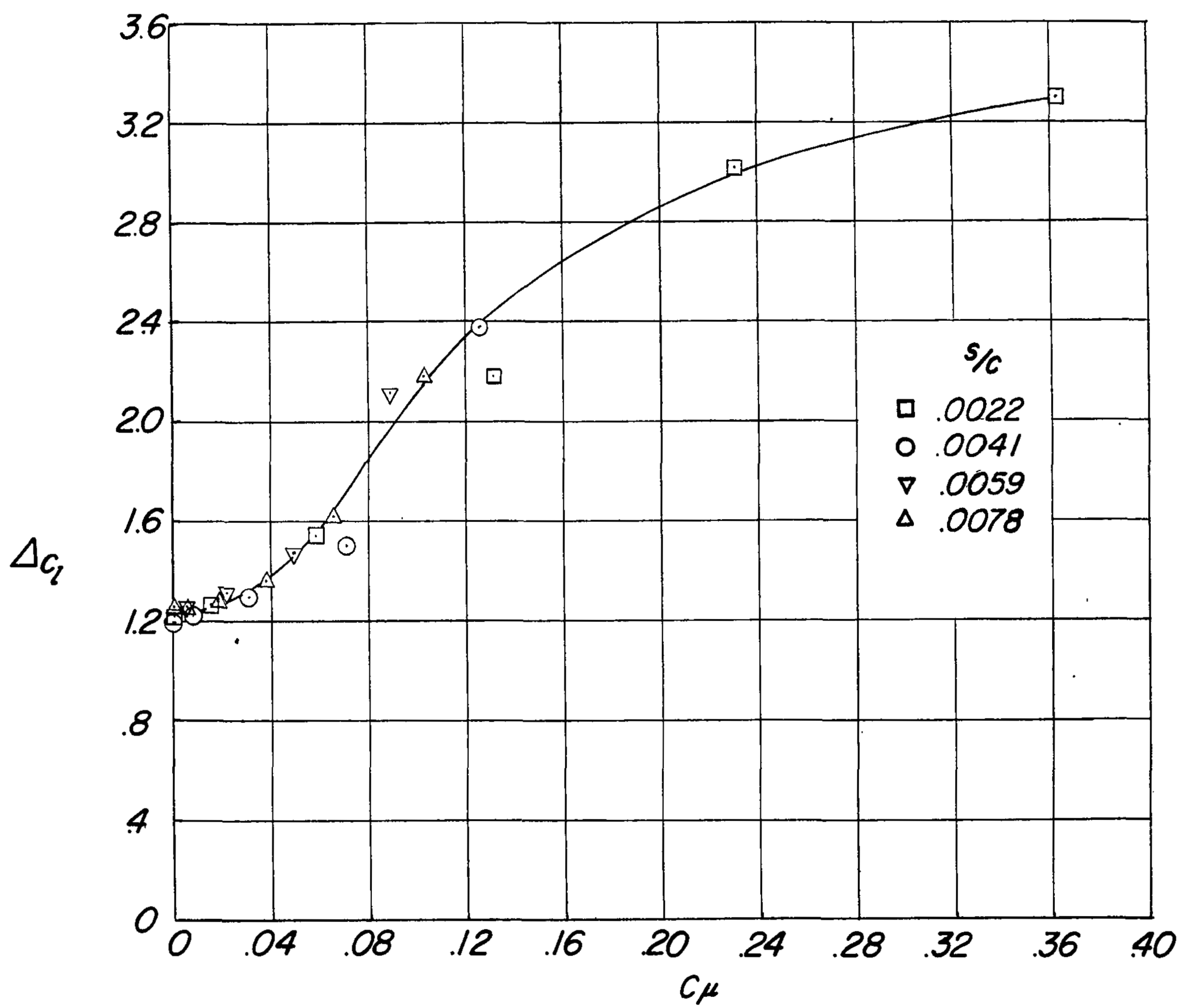


Figure 11.- Effect of slot width on a blowing flap of approximately 0.25c. $\delta_f = 50^\circ$; $\alpha = 10^\circ$ (ref. 21).